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Development of methodology for calibrated simulation in single-family residential buildings using three-parameter change-point regression model

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ABSTRACT

This study developed a methodology for a calibrated simulation of single-family residential buildings using a three-parameter change-point regression model. This new method provides a reproducible systematic and consistent calibration procedure. The procedure consists of two parts: a sensitivity analysis that can analyze the characteristics of the building; and a calibration procedure that uses the results of the sensitivity analysis. In the first part, the characteristics of the case-study house were analyzed using a detailed sensitivity analysis with a three-parameter change-point regression model. In this procedure, the most to least influential parameters for each three-parameter coefficient for the house were identified. Next, the identified parameters for each three-parameter coefficient were adjusted to closely match the actual building energy use of the house. Using the procedure, the 36.9% global CV (RMSE) of the initial simulation was improved to 8.8% after calibrated simulation, which is within the accuracy criterion according to the ASHRAE Guideline 14-2014. This study was conducted using a case-study house in a hot and humid climate. However, the procedure developed should be useful for other climates as well. In addition, the results of calibrated simulation can help determining energy efficient measures that are appropriate for the house in the future.

1. Introduction

In general, the simulated energy use of an existing residential building modeled using a building energy simulation program have large differences when compared with actual energy use of the house. For this reason, the simulation of the building should be tuned or calibrated by adjusting the appropriate input values to more closely match the actual building energy use. This process is commonly called calibrated simulation. Calibrated simulation can more accurately predict energy savings for future energy efficiency retrofits of the building because the calibrated simulation reflects the current building condition such as the deterioration of the air conditioner efficiency, etc. In addition, the accuracy of a calibrated simulation can vary from one simulation user to another because it relies heavily on the users' level of skill and knowledge in both the use of the simulation, practical knowledge about building operation, and ability to calibrate the simulation model.

Several calibrated simulation methodologies has been studied since the 1970s, which were summarized by Reddy [1]. According to Reddy, the methodologies can be divided into four approaches, which include: (i) calibration based on manual, iterative, and pragmatic intervention; (ii) calibration based on a suite of informative graphical comparative displays; (iii) calibration based on special tests and analytical procedures; and (iv) analytical/mathematical methods of calibration. A number of studies in each approach have been reviewed, including: (i) the manual, iterative, and pragmatic intervention methods that were the most popular approach for the calibrated simulation. For example, Diamond and Hunn [2] conducted one of the first calibrated simulations by comparing the results of DOE-2 simulation with monthly utility data for an entire year in seven sets of commercial buildings in the late 1970s. A few years later, Kaplan et al. [3,4] calibrated small office building simulations using the monitored energy data for short periods in the heating and cooling seasons. They suggested that for the calibration procedure, one of the first step is to correct the obvious simulation errors such as unreasonable default values used by the simulation, then correct internal loads and other inputs. Hunn et al. [5] also calibrated a DOE-2.1d model for the Texas Capitol building

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Nomenclature

AFUE	annual fuel utilization efficiency
AMY	actual meteorological year
CV-RMSE	coefficient of variation of root mean squared error
CV-STD	coefficient of variation of standard deviation
EF	energy factor
IMT	inverse modeling toolkit
L&E	lighting and equipment
NCDC	national climatic data center
NMBE	normalized mean bias error
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
TMY3	typical meteorological year, version 3
WWR	window-to-wall ratio
3PC or 3PH	3-parameter cooling or heating

by generating normalized electricity use schedules for typical day types for the building. In addition, Haberl and Bou-Saada [6] studied the calibrated simulation for weather-dependent loads, which included space heating and cooling; (ii) in the second approach, informative graphical displays for calibrated simulation were used to show the differences between the simulated and measured energy use to help simulation users in deciding which parameters to calibrate for the next iteration. Bronson et al. [7] developed comparative three-dimensional graphics for a case-study building, Haberl et al. [8] developed the plots to help calibrated simulations such as the contoured density plots of energy use that can provide the users an improved perception of the central tendency of a cloud of data points, which included time-sequenced, surface density plots of energy use that added time sequencing of the contoured density plots of energy use; (iii) in the third approach, the special tests and analytical procedures using specialized approaches for calibrated simulation, including short-term energy monitoring test and signature analysis method were developed. Manke and Hittle [9] conducted short-term energy monitoring for small commercial buildings. In this study, they calibrated the simulation model using parameter sensitivity tests. They used the root mean squared error (RMSE) and total building energy use over the test period to compare the model to the energy use. In addition, Liu and Claridge [10] developed characteristic calibration signatures that are parametric sensitivity analysis plots that are helpful in the determination of which simulation input parameter needs to be adjusted and by what amount; (iv) in the fourth approach an analytical/mathematical method of calibration, Sun and Reddy [11] proposed a general analytic framework for calibrating an office building energy simulation through mathematical and statistical basis using DOE-2 program.

Although the methods in previous approaches help building energy simulation calibration process easily and accurately, they still require an advanced simulation users' knowledge in the simulation program and knowledge of building operation to calibrate the simulation. Therefore, the purpose of this study was to make the calibrated simulation process more effective by providing the users with a systematic and consistent procedure for more easily and accurately simulating single-family residential buildings. This methodology has another advantage of reducing time and effort of the users during the calibrated simulation process by separating the simulation parameters into weather-independent and weather-dependent groups using three-parameter coefficients that have physical meanings. In addition, the methodology enables the users to accelerate making decision which parameter to adjust next by providing the most significant parameter during the calibration process, which further saves time and effort of the users. These features can be an advantage of this methodology against other existing methodologies.

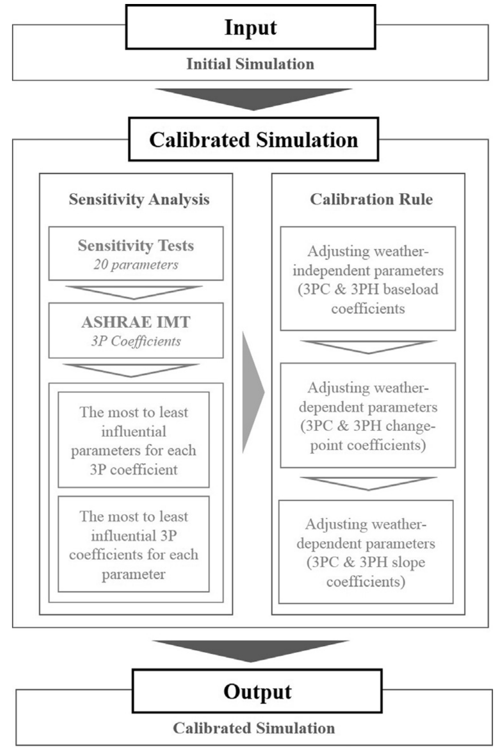

Fig. 1. The overall flow of calibrated simulation procedure.

This study is organized by the following five sections: (i) introduction and purpose of this study; (ii) calibrated simulation methodology; (iii) calibrated simulation for a first case-study house, including sensitivity analysis using a three-parameter change-point regression model; and (iv) calibrated simulation for a second case-study house; and (v) conclusion and discussions.

2. Methodology

The overall flow of the developed procedure of calibrated residential simulation is shown in Fig. 1. This methodology consists of two procedures, which include a sensitivity analysis that can analyze the characteristics of the building, and the calibrated simulation procedure that uses the results of the sensitivity analysis.

3. Calibrated simulation for a first case-study house

3.1. Sensitivity analysis using a three-parameter change-point regression model

3.1.1. Three-parameter change-point model

The ASHRAE inverse modeling toolkit (IMT) [12] was used for calculating the three-parameter change-point regression models in this study. The IMT is mostly used for building energy analysis for weather-normalization. The three-parameter change-point regression model is appropriate for analyzing single-family residential energy use that is strongly influenced by outside weather conditions due to heat gain or heat loss through walls and windows, and air infiltration through the building surfaces. Fig. 2 shows three-parameter change-point models for: (a) electric cooling and (b) natural gas heating as a function of outdoor air temperature.

Electricity use for a three-parameter change-point regression model of building can be calculated from Eq. (1). This equation describes the electricity use of a building as a constant (i.e.,